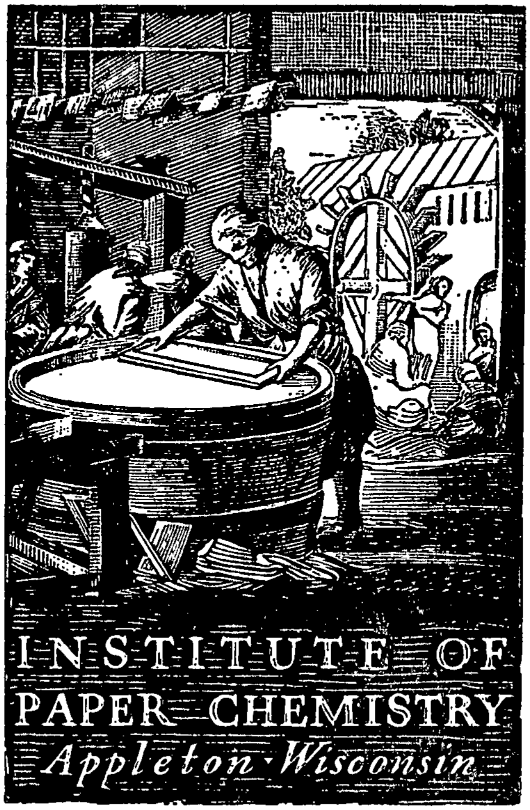
Van Eperen



DEVELOPMENT OF INSTRUMENTS AND TECHNIQUES FOR PULP EVALUATION: BONDING STRENGTH OF PULP. II. A STUDY OF THE STRESS CONCENTRATION EFFECTS IN THE z-DIRECTION TENSILE TEST

Project 2211

Report Seven

A Progress Report to

MEMBERS OF GROUP PROJECT 2211

November 5, 1963

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

DEVELOPMENT OF INSTRUMENTS AND TECHNIQUES FOR PULP EVALUATION: BONDING STRENGTH OF PULP. II. A STUDY OF THE STRESS CONCENTRATION EFFECTS IN THE z-DIRECTION TENSILE TEST

Project 2211

Report Seven

A Progress Report

to

MEMBERS OF GROUP PROJECT 2211

November 5, 1963

From: T. A. Howells, Project Administrator

To: Members of Group Project 2211

There is a continuing need for an adequate method of measuring fiber-to-fiber bonding so that results can be expressed in absolute units. For some years, relative comparisons have been made with various techniques such as the I.P.C. bonding strength tester (VVP). Encouraging results have been obtained with a transverse (z-direction) tensile test and further investigations of the significance and the limitations of this technique were covered in Report 4 (May 15, 1962). Modifications in technique were made to improve the control of the adhesive film, the alignment of the cylinders, the loading during assembly and the penetration of the adhesive. z-Tensile was found to increase with increasing specimen size up to a diameter of about 3/4 of an inch. A pronounced dependence of the results on basis weight was found, with the z-tensile decreasing with increasing sheet weight. This dependence was attributed to stress concentration effects.

The current report describes a continuation of this investigation in an attempt to determine whether these stress concentration effects can be handled so as to permit a more valid bonding strength measurement. One approach involved the use of higher compacting pressures, particularly during drying, and some interesting observations are reported on the effect of these conditions on the extensibility, opacity, and other characteristics of the handsheets.

MEMBERS OF GROUP PROJECT 2211

Albemarle Paper Manufacturing Company
Badger Paper Mills, Inc.
Blandin Paper Company
Champion Papers, Inc.
The Chesapeake Corporation
Consolidated Papers, Inc.
Crossett Division, Georgia-Pacific Corporation
Crown Zellerbach Corporation
Diamond National Corporation
East Texas Pulp and Paper Company
Eastman Kodak Company
The Eaton-Dikeman Company
Fox River Paper Corporation
P. H. Glatfelter Co.
Great Northern Paper Company
Hudson Pulp & Paper Corp.
Inland Container Corporation
International Paper Company
KVP Sutherland Paper Company
Kimberly-Clark Corporation
Knowlton Brothers
Longview Fibre Company
Marathon, A Division of American Can Company
The Mead Corporation
Michigan Carton Company
Minnesota Mining and Manufacturing Company
Minnesota and Ontario Paper Company
Mohawk Paper Mills, Inc.
National Vulcanized Fibre Co.
Nekoosa-Edwards Paper Company
The Northwest Paper Company
Oxford Paper Company
Packaging Corporation of America
Potlatch Forests, Inc.
The Procter & Gamble Company
Riegel Paper Corporation
Riverside Paper Corporation
St. Regis Paper Company
Scott Paper Company
Simpson Lee Paper Company
Sonoco Products Company
Thilmany Pulp & Paper Company
Union Bag-Camp Paper Corporation
Union Mills Paper Manufacturing Co.
Wausau Paper Mills Company
West Virginia Pulp and Paper Company
Weyerhaeuser Company

TABLE OF CONTENTS

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

DEVELOPMENT OF INSTRUMENTS AND TECHNIQUES FOR PULP EVALUATION: BONDING STRENGTH OF PULP. II. A STUDY OF THE STRESS CONCENTRATION EFFECTS IN THE z-DIRECTION TENSILE TEST

SUMMARY

The work described in this report constitutes a continuation of that described in Progress Report Four; it was initiated to investigate the basis weight effect on z-direction tensile and then to determine whether it would be possible to cope with the stress concentration effects in a manner which would permit a more valid evaluation of the true bonding strength. For this investigation, a commercial tracing paper and pressure-dried handsheets, prepared from a classified western softwood bleached sulfite pulp (the fraction retained on a 150-mesh screen), were used. Working with the tracing paper, a paper of adequately high density to eliminate the penetration of adhesive, the effective test span was varied by grinding away portions of the sheet and thereby changing the thickness of the test specimen. An increase of only 4% in z-direction tensile was noted as the thickness of the sheet was reduced to approximately one-half its initial thickness. The result indicated also that the weakest zone of this commercial paper was at the midplane of the sheet. Both the wire-side half and the felt-side half of the sheet were considerably stronger (to the extent of approximately 18-30%) than the center-half of the sheet. For a pressure-dried handsheet, this trend was reversed and the center portion of the sheet was found to yield a significantly higher z-direction tensile result than either of the two outer portions of the sheet.

In an exploration of the effects of fiber segmental length and lumen bonding on the z-direction tensile result, a series of sheets were dried under

compacting stresses of 3.5, 21, 126, and 490 kg./sq. cm., respectively. The z-direction tensile per unit bonded area increased dramatically with increasing compacting pressures above 21 kg./sq. cm. In this region, the curves were too steep to permit a valid extrapolation to an intercept value of z-direction tensile per unit bonded area. This very large increase in z-direction tensile per unit bonded area suggests, as one possibility, that lumen bonding is initiated at the higher compacting pressures. Lumen bonding would be expected to reduce the flexing of the fiber wall and, consequently, the stress concentration. At the same time, there is evidence that the high compacting pressure has altered the sheet structure and, undoubtedly, the manner in which fiber segmental length contributes to stress concentration.

Work with the pressure-dried sheets has contributed to our understanding of sheet structure. These sheets displayed unusually high extensibility. Before stressing, they were unusually translucent and during stressing the opacity increased steadily and greatly. After tensile failure, the opacity was that of a normal dried sheet. This behavior is attributed to the more extensive conforming of fibers to each other as a result of the pressure drying.

INTRODUCTION

The z-direction tensile test described in Progress Report Four, May 15, 1962, is one of several procedures that have been suggested and tried in an effort to measure bonding strength. The test has been greatly modified and simplified under this program. The improved equipment now provides for more precise control of the adhesive film thickness, of the alignment of the cylinders, and of the compressive load that is applied to the specimen test assembly during the curing of the adhesive. The modified procedure yields z-direction tensile values at a higher level and with smaller variability than heretofore obtained. However, as reported in Progress Report Four, the result is highly dependent on the basis weight of the test specimen (i.e., it increases sharply with decreasing basis weight); this dependence was attributed to a microstress-concentration. According to theory, the flexing of fiber segments and of the fiber wall creates a stress concentration around the periphery of the bonded areas. Hence, the bond fails at an observed load that is much less than that corresponding to the true bond failure stress.

Since issuance of Report Four, work was initiated to investigate the basis weight effect and to determine whether it would be possible to cope with the stress-concentration effects in a manner which would permit a more valid observation of the true bonding strength. In pursuing this objective, two approaches were tried. In one, the effect of test span on z-direction tensile was explored with the expectation that a decrease in specimen thickness should increase the importance of the constraint of the adhesive on the surface fibers and decrease the flexing of fiber segments and the associated microstress-concentration. A high-density machine-made sheet was selected for this study with the view of eliminating adhesive penetration as a variable. The effective test span was varied by grinding away portions of the sheet, thereby changing the thickness of the test specimen without changing the internal sheet structure. As the work progressed, this study was extended to handsheets that were dried under a high compacting stress.

In the second approach, the effect of compacting stress during drying on z-direction tensile was explored. The sheet structure was varied by varying the extent of bonding and the fiber segmental lengths through the pressure drying of handsheets. Through development of a relationship between z-direction tensile (corrected for the relative bonded area) and the reciprocal of the compacting stress, it was of interest to determine whether an extrapolation of this relationship would lead to higher and presumably truer values of bonding strength.

Important observations on sheet structure and supplementary measurements were made. These observations and results are given in the following sections of this report.

DESCRIPTION AND PREPARATION OF SAMPLES

The samples used for this study consisted of a machine-made 100% rag tracing paper (Albanene—Keuffel and Esser Company) and three series of regular and pressure-dried handsheets as described below.

The handsheets were prepared from a Weyerhaeuser bleached softwood sulfite pulp that was refined by ball milling to a freeness of 700 cc. S.-R. and classified in a Bauer-McNett classifier. The fraction retained on a 150-mesh screen was used and this fraction had a freeness of 875 cc. S.-R. The fractionated pulp was dispersed in a British disintegrator for 7500 revolutions and all handsheets were made with equipment described in TAPPI method T 205 m-58.

Series 1 consisted of pressure-dried handsheets made at three different weights, approximately 60, 120, and 180 g./sq. m., i.e., 1, 2, and 3 times the weight of a regular TAPPI handsheet, and at compacting pressures in the range of 3.5 to 420 kg./sq. cm. (50-6000 p.s.i.). The sheets were couched directly onto a water-moistened blotter (to minimize the effect of blotter expansion on the sheet); these blotters were pretreated with an enamel (i.e., one surface of the blotter was lightly sprayed with an enamel paint and the paint was allowed to dry at 100°F. for several days before use) which served as a release agent to minimize bonding between the handsheet and blotter surfaces in the subsequent pressure drying but without seriously reducing the absorbency of the blotters. After couching, a moistened, pretreated blotter was placed over the exposed wire-side surface of the handsheet and the two pretreated blotters backed with five dry blotters (untreated). The sandwiched handsheet was then placed in a press between flat, smooth-surfaced steel platens of the same dimensions as the handsheets (when pressing several sheets at a time, which was usually the case, smooth-surfaced steel disks were also placed between adjacent sandwiches) and the desired compacting pressure was applied. Following drying intervals of 15 minutes, the compacting pressure was released momentarily to replace the "wet" blotters with a fresh dry set. For sheets subjected to compacting pressures of 3.5 kg./sq. cm., (50 p.s.i.) five 15-minute pressure drying intervals were used; for those dried at 35, 70 and 140 kg./sq. cm. (500, 1000, and 2000 p.s.i., respectively) four intervals were used; and for those dried at 280, 350, and 420 kg./sq. cm. (4000, 5000, and 6000 p.s.i., respectively) three intervals were used. Subsequently, the sheets were exposed directly to the testing atmosphere controlled at 50% R.H. and 73°F. Due to deep blotter impressions, the sheet surfaces for this series were quite rough.

Series 2 represented an attempt to improve the sheet smoothness and consisted of double-weight handsheets made in accord with TAPPI method T 205 m-58 and sheets pressure-dried between Millipore filters (Millipore Filter Corporation, Bedford, Massachusetts—220 mμ pore size) under compacting pressures in the range of 3.5 to 490 kg./sq. cm. (50-7000 p.s.i.). The sheets for pressure drying were couched directly onto a Millipore filter backed with one thickness of a water-moistened Whatman No. 1 filter paper. A Millipore filter backed with one thickness of a water-moistened Whatman filter paper was also placed on the wire-side of the handsheet and ten thicknesses of dry Whatman filter paper were placed on each side. The sandwiched handsheets were pressed twice at 3.5 kg./ sq. cm. (50 p.s.i.) and pressure-dried without interruption of the compacting pressure. The first pressing at 3.5 kg./sq. cm. was for a period of 5 minutes, the second for 15 minutes. Between pressings and following the second pressing, all Whatman filter papers, except the two adjacent to the Millipore filter, were replaced with dry filters. The first two pressings were used to adjust the moisture content of the sheet at a level of approximately 50% (based on wet weight). This level, according to Gallay, et al. (1) corresponds to the approximate threshold of bond formation. For the third and final pressing the sandwiched handsheets were placed in a press between flat, smooth-surfaced steel platens of the same dimensions as the handsheet and subjected to the desired compacting pressures. The contacting pressure was maintained, without interruption, for a period of 15 minutes. The moisture content of the sheets at the end of this drying period fell within the range of 10 to 15% which is safely below the moisture content level at which further bond formation is expected to occur (1). On completion of the final pressing, the sheets were exposed directly to the testing atmosphere of 50% R.H. and 73°F.

Series 3 consisted of single, double, and triple-weight sheets that were pressed and pressure-dried between Millipore filters as described for Series 2 but at a single compacting pressure of 126 kg./sq. cm. (1800 p.s.i.). For the single and double-weight sheets, the compacting pressure was maintained undisturbed for a period of 15 minutes; for the triple weight sheets, the compacting pressure was maintained undisturbed for 1 hour. After the final pressing, the sheets were exposed directly to the testing atmosphere.

TEST PROCEDURES

The z-direction tensile tests were performed in accord with the procedures described in Progress Report Four. Shell Chemical Company's Epon 907 was used as the adhesive. The adhesive was allowed to precure for a period of 20 minutes and was applied to the cylinder faces at a controlled thickness of 0.05 mm. (0.002 in.). After inserting a specimen between two adhesive-bearing cylinders, the specimen assembly was placed in the V-grooved alignment fixture and subjected to a compressive load of 0.4 kg./sq. cm. for a period of about 2 hours. At the end of this time, the specimen assembly was removed from the alignment fixture and set aside for about 18 hours for further curing of the adhesive. Subsequently, the z-direction tensile measurement was made with a Baldwin-Southwark universal testing machine, using a crosshead speed of 0.13 cm./min. (0.05 in./min.). For this measurement, the adhesive bead and the portion of the specimen protruding from the cylinders was not removed; however, the effective area of the bead was taken into account in calculating the result in terms of kg./sq. cm.

Further experiments on precuring time and film thickness were made and the results indicated that the film thickness could be reduced somewhat but that the precuring time could not exceed 30 minutes. At a precuring time of about 30 minutes, the adhesion to a high density, impenetrable paper, such as the tracing paper, is not good enough for this application.

The load-elongation curves were obtained with a Table Model Instron. From these, the tensile breaking load and the breaking strain were determined. The Instron was equipped with a set of IPC line-type specimen clamps (2) and it was operated at a crosshead speed (straining rate) of 2.54 cm./min. Test spans of 10.2 cm. and a specimen width of 1.5 cm. were used.

The relative bonded area (RBA) was determined through measurement of the optical scattering coefficients and calculated in accord with the following.

$$RBA = (1 - \underline{s}/\underline{s}_o) \qquad (1)$$

where $\underline{s}$ = the specific scattering coefficient for the "bonded" sheet in sq. cm./g.

$\underline{s}_o$ = the specific scattering coefficient for an "unbonded" sheet in sq. cm./g. as determined by extrapolation to zero strength of the z-direction tensile *vs.* scattering coefficient relationship.

The reflectance $\underline{R}_o$ of a single sheet backed with a black body and the transmittance $\underline{T}$, required for the determination of $\underline{s}$, were measured with a General Electric Recording Spectrophotometer at a wavelength of 550 mμ. These and the z-direction tensile measurements were made on the same specimens.

The opacity was determined with a Bausch and Lomb Opacimeter in accord with TAPPI method T 425 m-60.

The various specimen thicknesses for the tracing paper and the pressure-dried handsheets (Series 3), used in the study on the effect of test span, were obtained by means of a special grinding technique. Briefly, this technique involves the use of a typical machine shop surface grinder of the kind used for the surface grinding of steel. The specimen is placed on a smooth-surfaced steel vacuum hold-down plate. This plate is positioned on the bedplate of the grinder and is secured magnetically. A coarse-grained carborundum wheel is used. With the wheel rotating in a clockwise direction and positioned over the right-hand portion of the specimen, the wheel is lowered and brought into contact with the specimen. The position of the wheel is further adjusted to the desired grinding depth and a grinding pass is made by feeding the bedplate from left to right. Without changing the wheel's vertical position, the bedplate is returned to the left, and a second grinding pass is made with the wheel slightly overlapping the previous grinding path. Several additional grinding passes are made in a similar fashion to obtain specimens of the desired size. For the purpose of this study, the grinding was performed over a surface approximately 3 by 12 cm. For those cases in which both sides of a given specimen were ground, the second side was ground by merely repeating the procedure used for the first. The grinding was carried out in an unconditioned atmosphere. In order to maintain comparable moisture content histories for the ground and unground specimens, both were exposed to the same atmospheres.

RESULTS AND DISCUSSION

EFFECT OF TEST SPAN

The results obtained for various thicknesses and portions of the tracing paper in studying the effect of test span are given in Table I and Fig. 1. In the table, Column 1 identifies the grinding conditions used in production of the test specimens; Column 2 gives the percentage by weight of the portion of the sheet retained for the z-direction tensile measurement; and Colums 3, 4, 5, and 6 give the corresponding basis weights of the test specimens, the thickness, density, and z-direction tensile, respectively. In Fig. 1, the various portions of the sheet involved in the measurement are illustrated by the hatched areas. The average basis weights are given and the corresponding z-direction tensile values appear within the hatched areas.

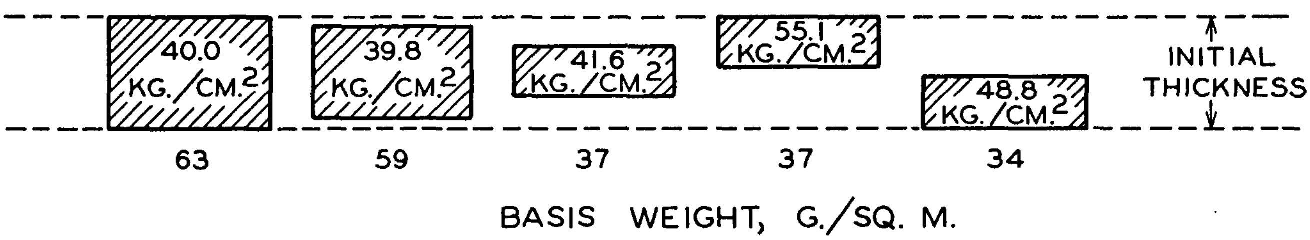


Figure 1. z-Direction Tensile for Sections of a Tracing Paper

On examination of the data given in Table I and Fig. 1, it will be noted that measurements made on the whole sheet and on specimens symmetrically ground on the two surfaces yielded z-direction tensile values of 40.0, 39.8, and 41.6 kg./sq. cm., an increase of only 4% on going to a test span corresponding to half the thickness of the specimen. This unexpected small increase with decreasing span prompted further study which would permit comparing the center portion of the sheet with portions taken from the two sides. The results

TABLE I

EFFECT OF TEST SPAN ON z-DIRECTION TENSILE FOR A 100% RAG TRACING PAPER—SPAN VARIED BY GRINDING AWAY PORTIONS OF SHEET

Sheet Condition	Portion of Sheet Retained, %[a]	Basis Weight,[b] g./sq. m.	Thickness, microns	Density, g./cc.	z-Direction Tensile, kg./sq. cm.
Unground	100	63	69	0.92	40.0
Ground both sides	94	59	56	1.05	39.8
Ground both sides	59	37	30	1.23	41.6
Ground on side 1	59	37	32	1.16	55.1
Ground on side 2	54	34	31	1.10	48.8

[a]Percentage based on initial unground weight of the sheet.

[b]Based on airdry weight at 50% R.H. and 73°F.

Each z-direction tensile value represents the average of 8 determinations.

of these measurements, obtained for specimens of essentially the same thickness, indicated that the two outer halves of the sheet are apparently stronger than the "center." Since the "weak center" rendered this specific sample of tracing paper unsuitable for the purposes of this study, work with this sample was abandoned, and a similar exploratory study was made using the pressure-dried handsheets of Series 3 (couched, pressed and dried between Millipore filters at 126 kg./sq. cm.). These results are given in Table II and Fig. 2 with the format the same as Table I and Fig. 1.

On examination of the data given in Table II and Fig. 2 for double and triple-weight pressure-dried sheets, it will be noted that, for any given sheet, measurements made on the whole sheet and on specimens ground symmetrically from the two sides yielded z-direction tensile values of about the same order of

TABLE II

EFFECT OF TEST SPAN ON z-DIRECTION TENSILE FOR PRESSURE DRIED HANDSHEETS, SERIES 3—SPAN VARIED BY GRINDING AWAY PORTIONS OF SHEET

Sheet Condition	Portion of Sheet Retained, %[a]	Basis Weight,[b] g./sq. m.	Thickness, microns	Density, g./cc.	z-Direction Tensile, kg./sq. cm.
Unground	100	67	94	0.77	56.0
Ground both sides	93	62	66	1.00	55.9
Unground	100	148	165	0.97	33.1
Ground both sides	98	145	134	1.17	34.6
Ground on wire side	73	108	100	1.17	14.2
Ground on nonwire side	76	112	95	1.29	18.2
Unground	100	204	218	1.01	33.1
Ground both sides	82	167	141	1.28	27.7
Ground both sides	53	109	88	1.34	33.6
Ground both sides	43	87	68	1.40	32.2
Ground on wire side	71	144	120	1.29	19.2
Ground on wire side	43	88	72	1.32	21.3
Ground on nonwire side	70	143	122	1.27	18.9
Ground on nonwire side	49	100	79	1.36	24.1

[a]Percentage based on initial unground weight of the sheet.

[b]Moisture-free basis.

Each z-direction tensile value represents the average of 3 determinations.

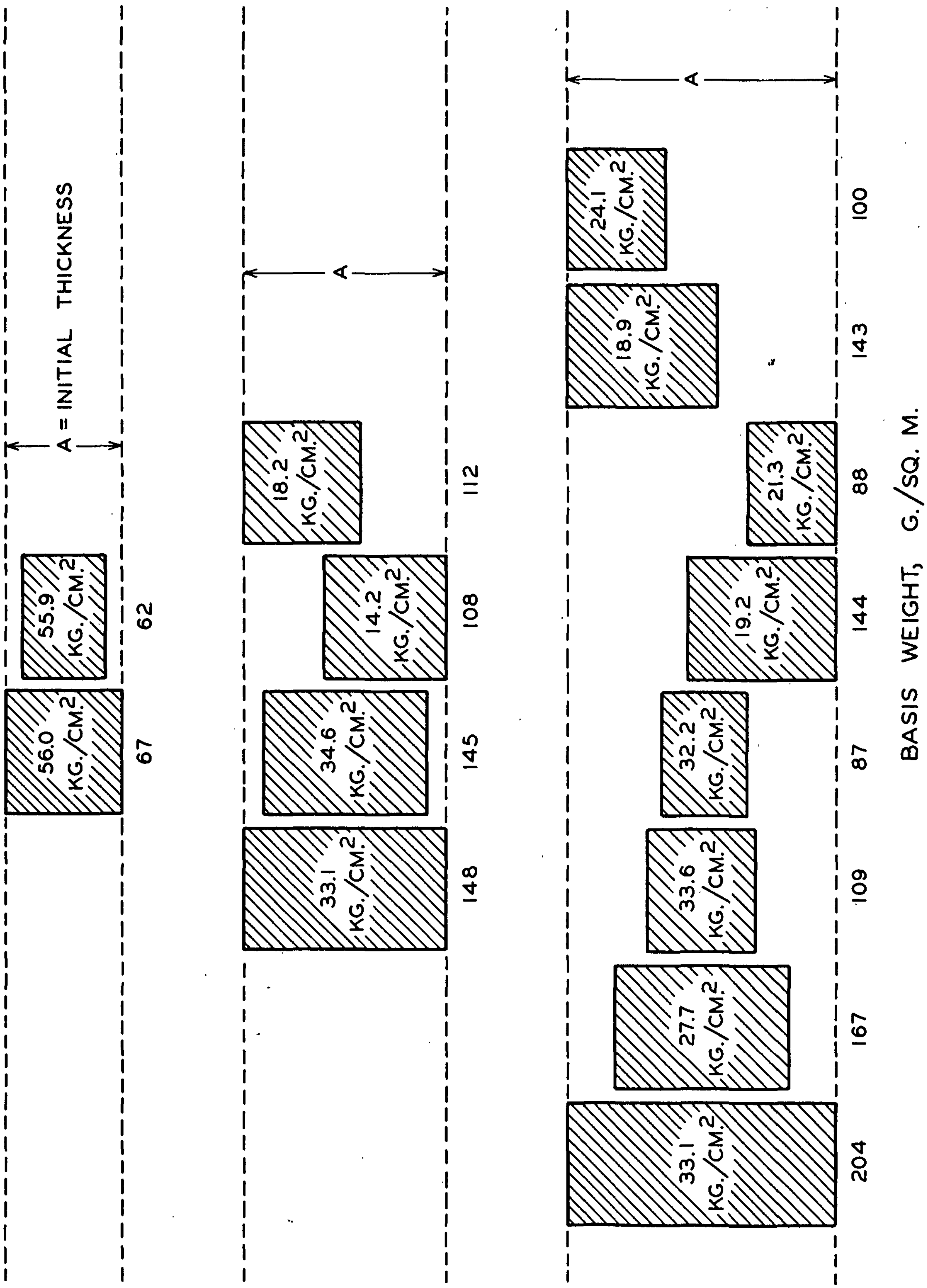


Figure 2. z-Direction Tensile for Sections of Pressure-Dried Handsheets, Series 3

magnitude and independent of the specimen thickness. This result is not in accord with the behavior one would expect on the basis of stress concentration effects. However, in contrast to the results obtained for the tracing paper, these for the handsheets show that the center of the sheet is apparently much stronger than either side. Inasmuch as the weaker sides are involved in the testing of the whole sheet, it would appear that the failure in the z-direction tensile test does not necessarily occur in the weakest zone of the sheet. Failure at the mid-plane was observed for all specimens involved in these measurements, irrespective of thickness. Apparently, the stress concentration effect, which is maximum at the mid-plane of the specimen, predominates and causes the specimen to fail at its mid-plane even though weaker zones exist away from the mid-plane of the specimen.

On further examination of the data given in Tables I and II, it seems of interest to note that a light grinding on the two sides of the sheet apparently introduced no adverse effect on z-direction tensile. Furthermore, the grinding evidently produced sufficiently smooth and parallel surfaces to uncover a significant "error" inherent in the usual thickness measurement of unground specimens. Judging from the increase in sheet density on going from unground to lightly ground specimens it would appear that this error is of the order of 15 to 30%. It also seems of interest to note that the "center" of the triple-weight pressure-dried handsheet had the high density of 1.4 g./cc., as compared with the density of the pulp fiber wall, at about 1.55 g./cc. This indication of low void volume and small interstitial spacing between fibers was confirmed visually. When the whole sheet was viewed by transmitted light under magnification, no individual fibers could be identified and there appeared to be very little scattering of light in the internal structure of the sheet; the scattering that was observed appeared to originate chiefly at the two surfaces of the sheet.

EFFECT OF COMPACTING STRESS

The results obtained in studying the effect of compacting stress during drying on z-direction tensile are given in Tables III and IV and Fig. 3-6. In each table, data on pertinent sheet properties are given for the purpose of characterizing the sheets. In addition, Columns 8 through 12 of Table IV give the opacity before and after straining, the specific scattering coefficient, the relative bonded area, and the z-direction tensile per unit bonded area.

On examining, first of all, the results obtained for the purpose of characterizing the sheets, it will be noted that the drying of the sheets at high compacting stresses introduced several significant changes. In general, it is observed that the tensile breaking load increased about 30% with increasing compacting stresses up to about 140 kg./sq. cm. and then tended to level-off at the higher stress levels; the breaking strain increased about 30 to 60% with increasing stress, tended to reach a maximum in the range of 70 to 140 kg./sq. cm. and decreased with increasing stress beyond this range; and the opacity decreased sharply for stress levels above 21 kg./sq. cm.

On straining the more highly translucent sheets to failure it was visually observed that the opacity increased gradually with increasing strain in a remarkably uniform manner over the whole area of the specimen. As the specimen approached the breaking strain and tensile failure, it exhibited the general appearance of a typical nonpressure dried handsheet. As may be seen in Table IV, the opacity after straining to failure was essentially restored to that of the normally dried handsheet. Along with the foregoing, it was also observed that the load-elongation characteristics for the pressure-dried sheets departed significantly from those normally observed for typical TAPPI handsheets.

TABLE III

EFFECT OF PRESSURE DRYING ON z-DIRECTION TENSILE AND OTHER SHEET PROPERTIES FOR THREE LEVELS OF BASIS WEIGHT, SERIES 1

(Handsheets couched and pressure-dried between blotters)

Compacting Pressure During Drying, kg./sq. cm.	Basis Weight,[a] g./sq. m.	Thickness, microns	Density, g./cc.	Tensile Breaking Load,[b] kg./cm.	Breaking Strain, %	z-Direction Tensile, kg./sq. cm.
3.5	58	99	0.63	2.93	5.5	72.9
35	63	99	0.69	3.18	6.4	55.7
70	64	102	0.68	3.33	7.7	57.2
140	61	97	0.68	3.65	7.8	64.9
280	63	97	0.70	3.70	6.8	64.1
350	60	94	0.69	3.74	6.8	83.4
420	58	94	0.67	3.39	6.4	70.7
3.5	115	160	0.78	2.70	5.6	26.4
35	125	165	0.82	3.42	7.6	29.7
70	122	155	0.85	3.51	8.4	32.9
140	129	158	0.89	3.84	8.8	44.0
280	125	158	0.86	3.61	7.3	44.3
350	138	158	0.88	3.70	7.5	48.5
420	123	152	0.88	3.68	7.8	41.9
3.5	178	241	0.80	2.79	6.6	23.5
35	194	246	0.85	3.39	8.8	28.2
70	192	239	0.90	3.45	8.2	30.3
140	194	234	0.94	3.66	8.8	35.6
280	181	214	0.92	3.63	7.9	40.1
350	187	214	0.95	3.47	7.6	41.9
420	189	218	0.94	3.60	7.9	43.3

[a] Moisture-free basis.
[b] Reduced to kg./cm. for 60-g./sq. m. sheet.

Each z-direction tensile value represents the average of 5 determinations; each tensile breaking load and breaking strain value, the average of 2 determinations.

TABLE IV

EFFECT OF PRESSURE DRYING ON z-DIRECTION TENSILE, RELATIVE BONDED AREA AND OTHER SHEET PROPERTIES FOR ONE LEVEL OF BASIS WEIGHT, SERIES 2

Compacting Pressure During Drying, kg./sq. cm.	Basis Weight,[a] g./sq. m.	Thickness, microns	Density, g./cc.	Tensile Breaking Load,[b] kg./cm.	Breaking Strain, %	z-Direction, Tensile Strength, kg./sq. cm.	Opacity, %[c] Before Straining	Opacity, %[c] After Straining	Specific Scattering Coefficient, s, sq.cm./g.	RBA,[d] s_o=294[e]	z-Direction Tensile/RBA, kg./sq. cm. s_o=294[e]
f	122	162	0.82	3.32	5.1	19.1	76	81	165	0.439	43.5
3.5	129	163	0.86	3.15	6.7	21.6	76	82	150	0.490	44.1
21	124	159	0.84	3.45	6.8	21.4	74	82	146	0.504	42.4
126	141	162	0.94	3.50	7.9	32.6	57	79	76	0.742	43.9
490	132	153	0.93	3.49	6.7	42.6	43	73	52	0.823	51.7

[a] Moisture-free basis.
[b] Reduced to kg./cm. for 60-g./sq. m. sheet.
[c] Determined as contrast ratio on specimens used for determination of tensile breaking load and breaking strain, before and after straining to failure.
[d] RBA is the relative bond area, calculated as $(1-s/s_o)$.
[e] The extrapolated value of 294 sq. cm./g. was determined from the z-direction tensile-specific scattering coefficient relationship.
[f] Wet pressed and dried on rings in accord with TAPPI method T 205 m-58; all others couched, pressed, and dried between Millipore filters.

Each z-direction tensile value represents the average of 4 determinations; each tensile breaking load and breaking strain value, the average of 2 determinations.

The specific scattering coefficient and z-direction tensile measurements were made on the same specimens.

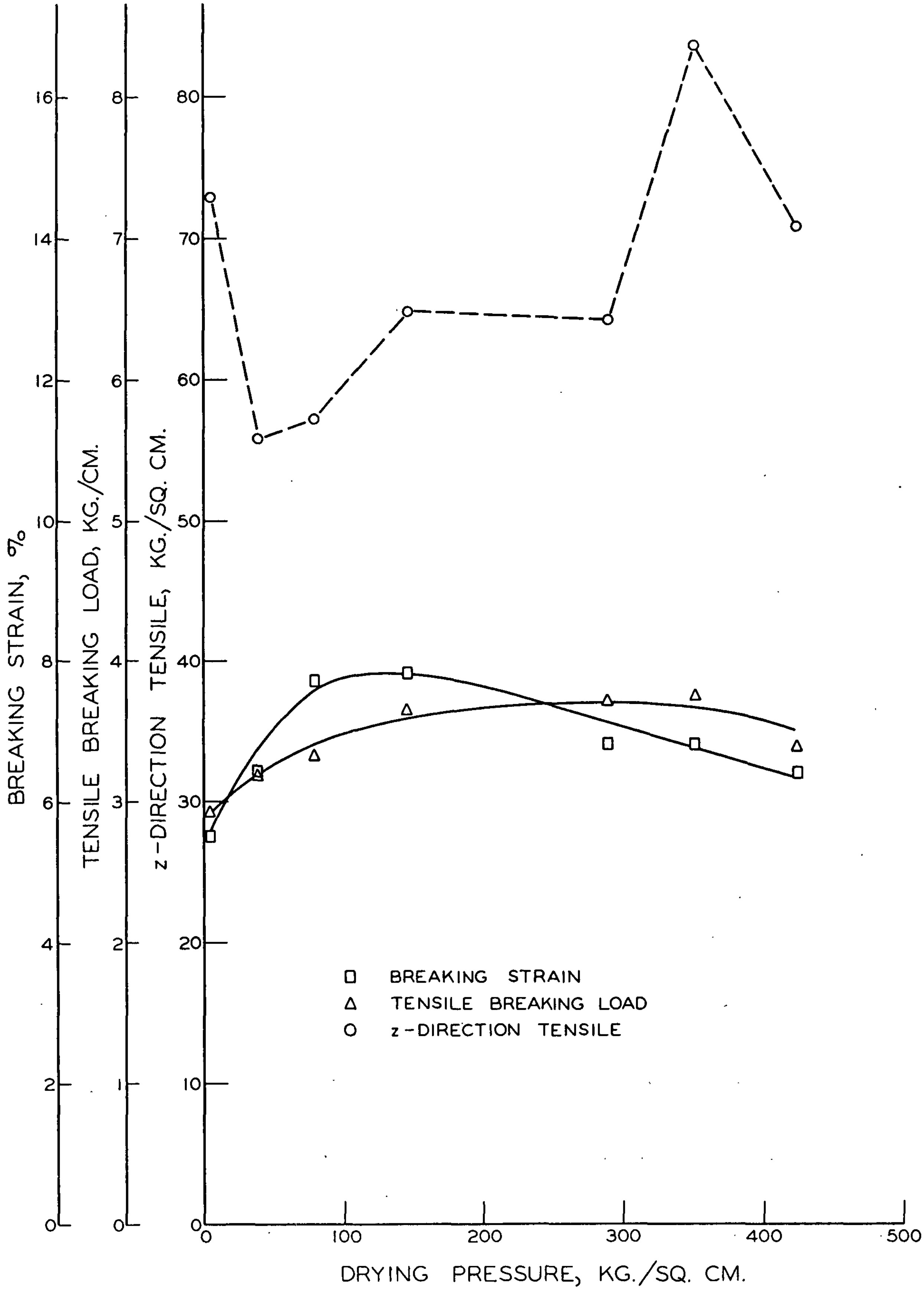


Figure 3. Relationship of Compacting Pressure During Drying to z-Direction Tensile, Tensile Breaking Load, and Breaking Strain for Single-Weight Handsheets, Series 1

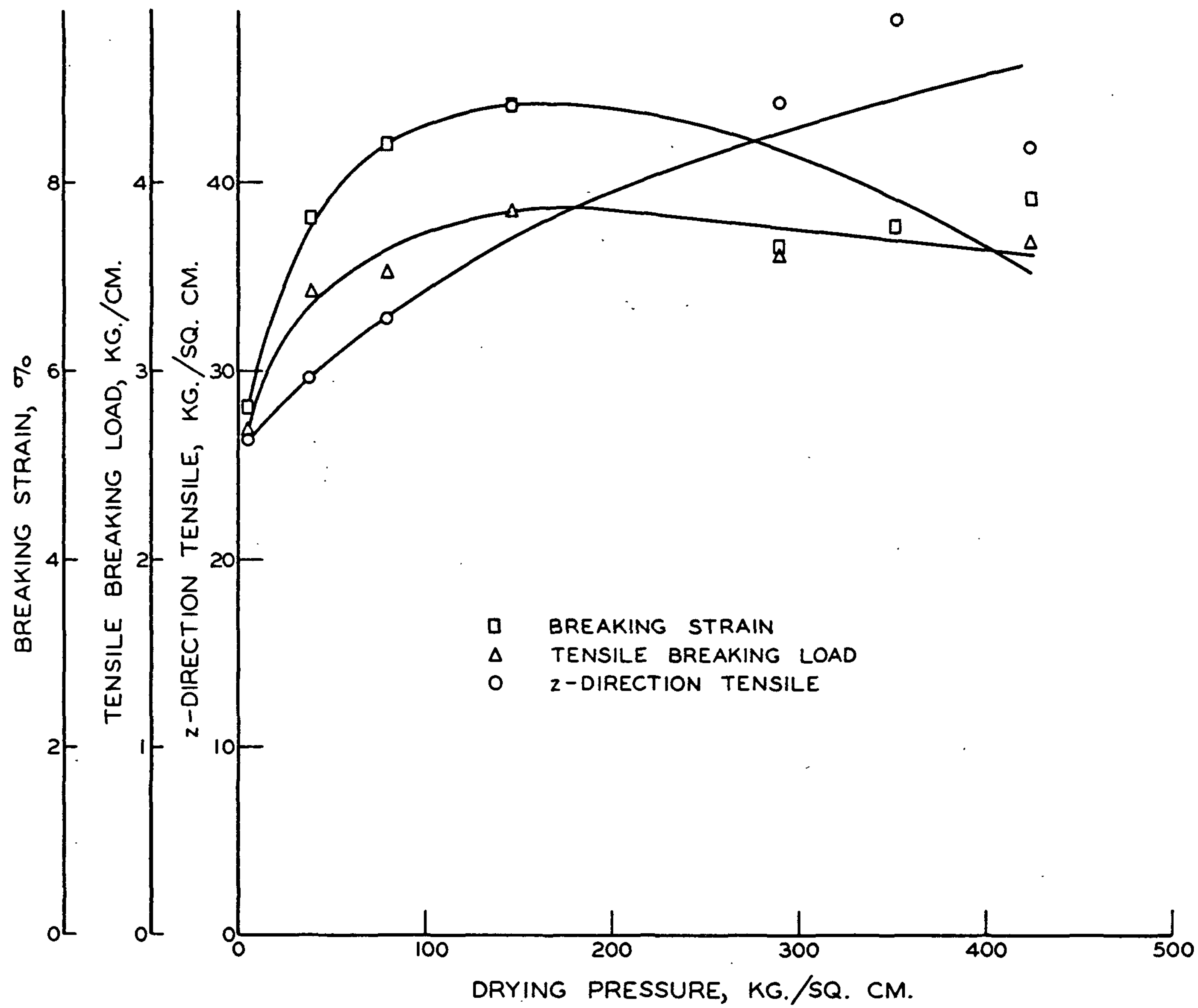


Figure 4. Relationship of Compacting Pressure During Drying to z-Direction Tensile, Tensile Breaking Load, and Breaking Strain for Double-Weight Handsheets, Series 1

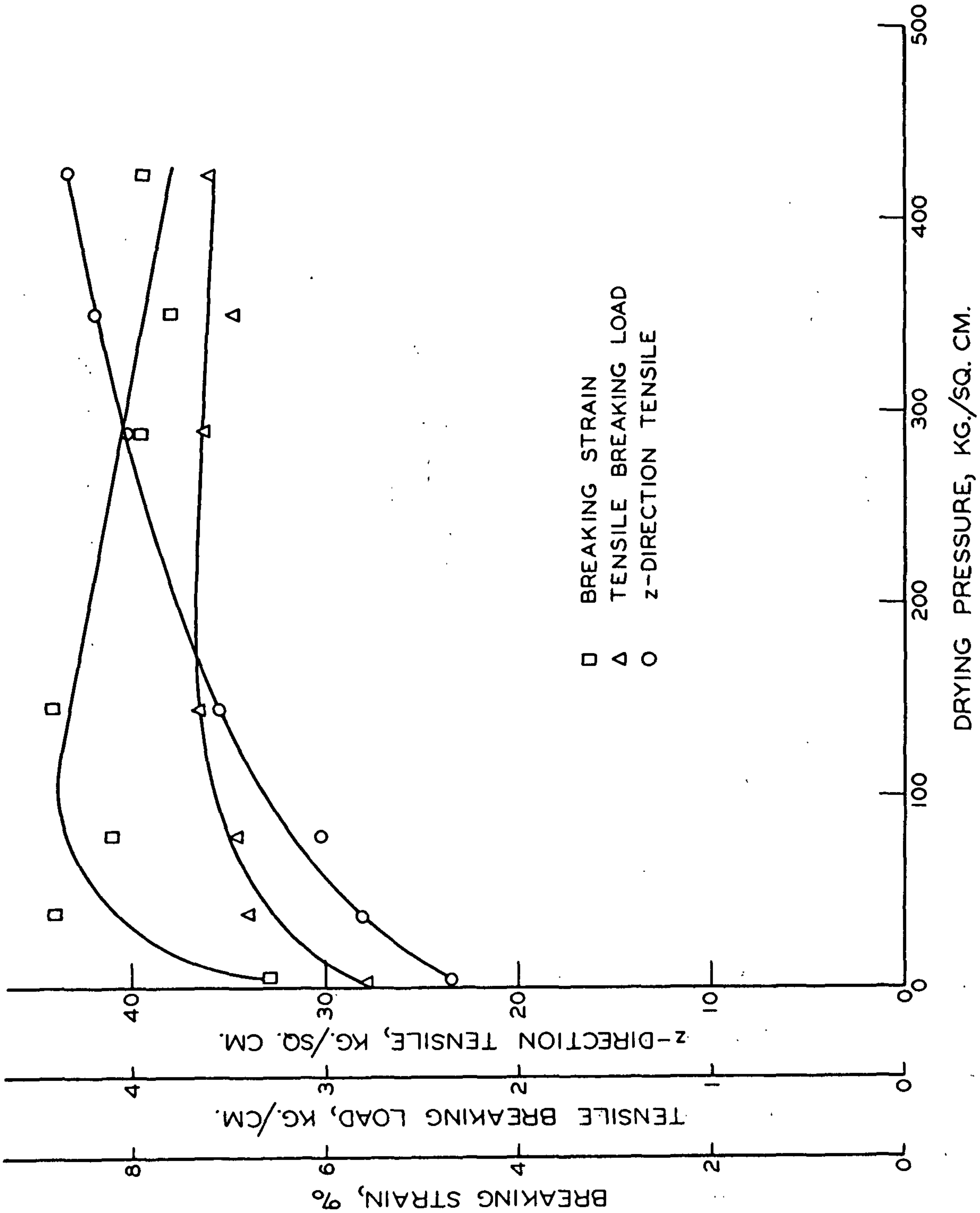


Figure 5. Relationship of Compacting Pressure During Drying to z-Direction Tensile, Tensile Breaking Load, and Breaking Strain for Triple-Weight Handsheets, Series 1

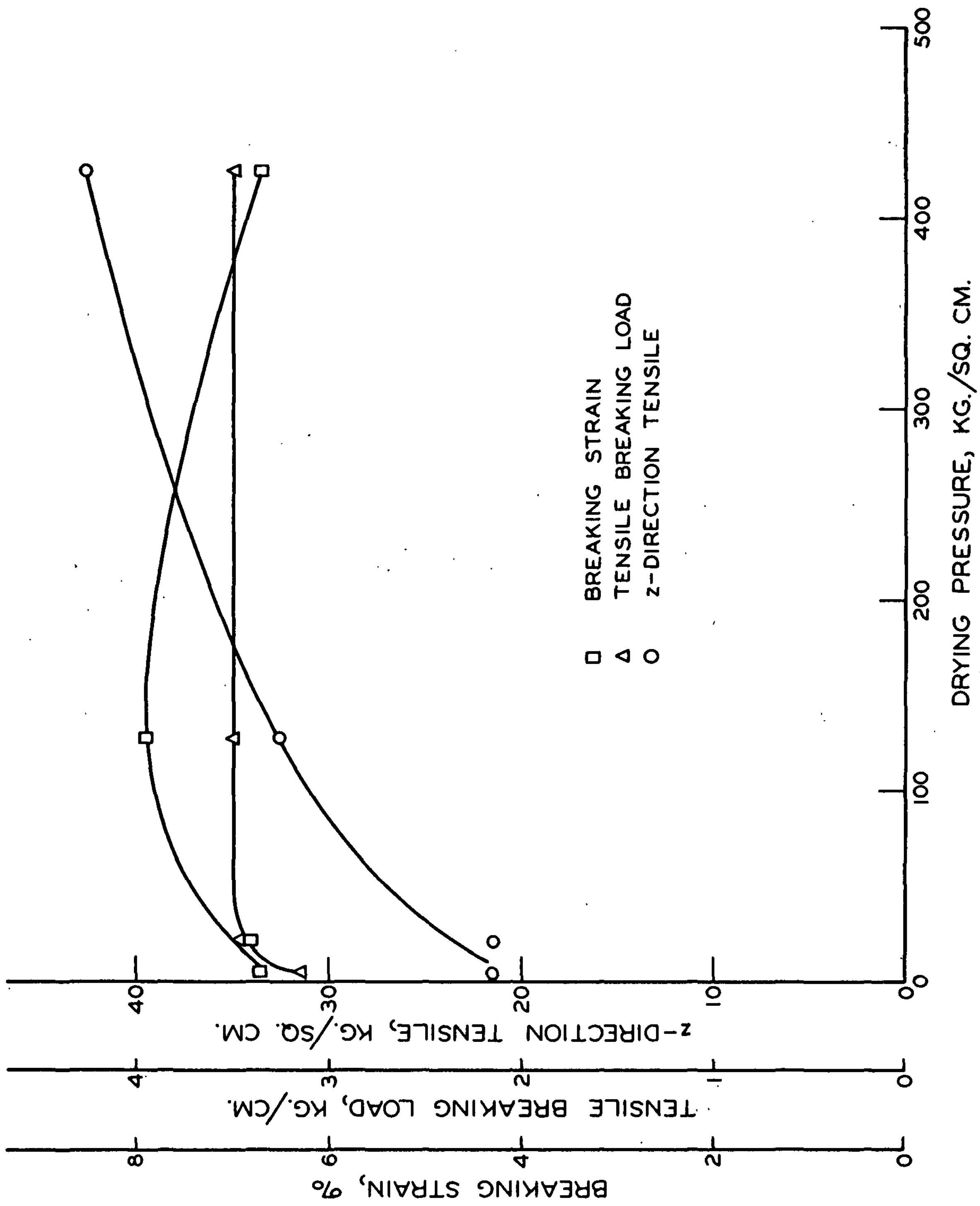


Figure 6. Relationship of Compacting Pressure During Drying to z-Direction Tensile, Tensile Breaking Load, and Breaking Strain for Double-Weight Handsheets Dried Between Millipore Filters, Series 2

Typical load-elongation curves for regular and pressure-dried handsheets are shown in Fig. 7. It will be seen that the curve for the pressure-dried sheet exhibits characteristics approaching those commonly found in "extensible papers."

The observations concerning the dramatic increase in opacity with strain and the nature of the load-elongation curves for the pressure-dried sheets would seem to offer important information concerning our understanding of sheet structure. Evidently, the drying of the sheets under a sustained compacting stress leads to a more extensive deforming of the fibers and conforming to each other. Consequently, the bonding is more extensive around the "sides" of fibers. On straining the sheet, the bonds at the sides of fibers presumably fail first. As a consequence, scattering surfaces are created, the opacity increases and the straightening-out of fiber segments contributes to the extensibility of the sheet.

Failure to achieve a uniform development in z-direction tensile with increasing compacting stress for the lightest and intermediate weight sheets of Series 1 is attributed to several factors. It is recalled that this series of sheets was dried between blotters and that these were changed several times during drying. Thus, the compacting stress may have been interrupted at a time when the moisture content was in the critical range of bond formation. It was also observed that the sheets contained heavy blotter impressions. These could result in irregularities in the adhesive film and, consequently, in an enhancement of stress concentration. The handsheets dried between Millipore filters, Series 2, represent the effort made toward improved control of the sheet-forming process and the development of sheets with improved smoothness.

Using the data obtained for the improved sheets, given in Table IV, an attempt was made to determine whether correcting the z-direction tensile for

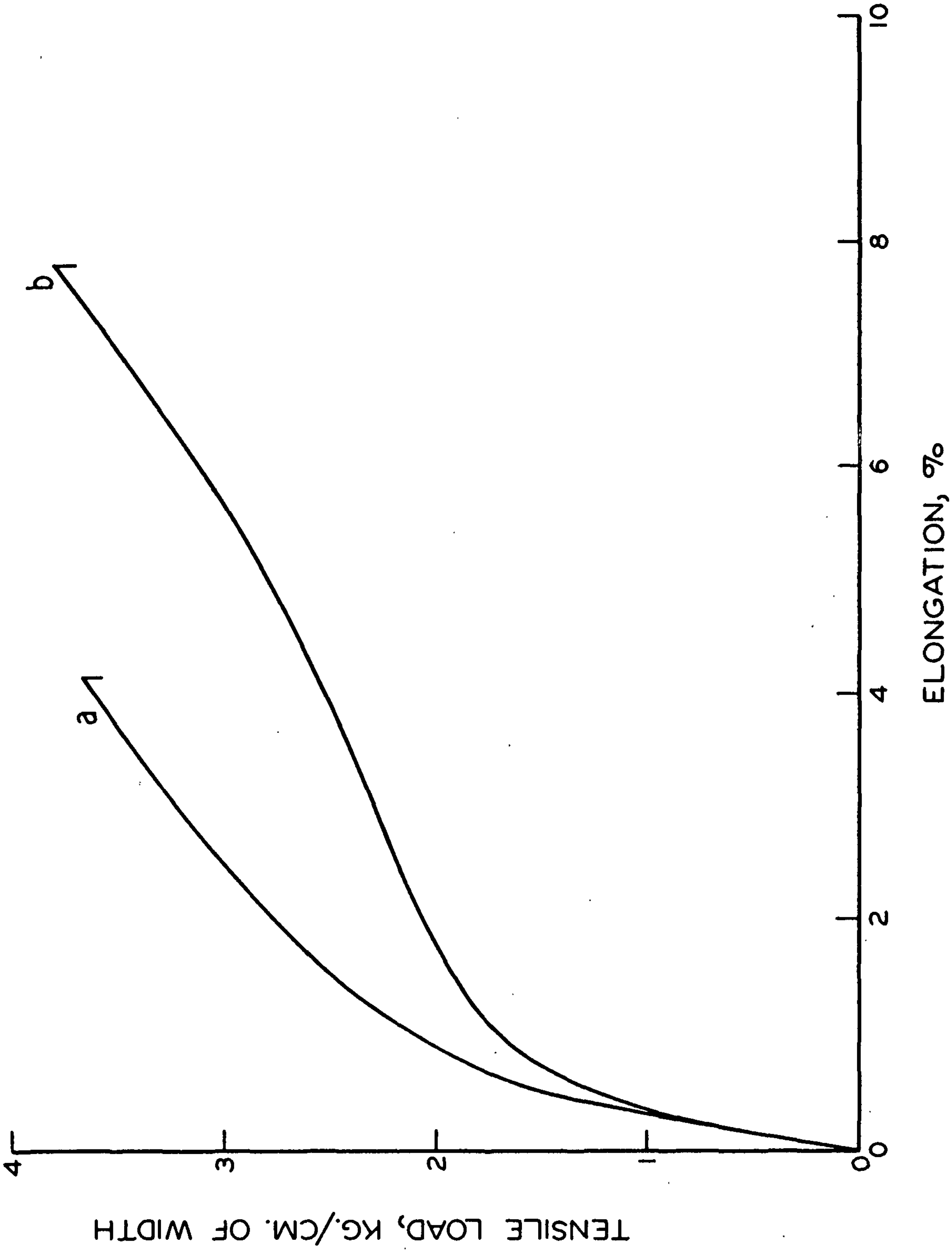


Figure 7. Typical Load-Elongation Curves for Handsheets Formed in Accord with TAPPI Method T 205, Curve a, and for Handsheets Dried Under a Compacting Pressure of 140 kg./sq.cm., Curve b

relative bonded area would lead to a value that could be interpreted as the true bonding strength for the specific pulp used in this study. Relative bonded area has been calculated in various ways, and two possibilities were tried. The specific scattering coefficient for the "bonded sheets" was plotted as a function of both the z-direction tensile and of the tensile breaking load for the purpose of determining the specific scattering coefficient for the "unbonded" sheet. The former plot is shown in Fig. 8. The variations in tensile breaking load were so small as to make an extrapolated value very questionable. The value of 294 sq. cm./g., obtained by extrapolation of the z-direction tensile data, is in fair agreement with previous values (based on tensile breaking load) obtained for this pulp (see Project 1513, Report 25, p. 11, 13, and 15), and only this value was used at the moment for calculating the relative bonded area.

Figure 9 presents a plot of the z-direction tensile per unit bonded area plotted as a function of the reciprocal of the drying pressure in the hope of extrapolating to a measure of "ultimate bond strength." Here, it will be seen that the z-direction tensile per unit bonded area remains fairly constant over a broad range of compacting stresses but that it increases sharply with higher stress levels (lower reciprocal values). As one possibility, this sharp increase suggests that lumen bonding is initiated at the higher compacting stresses. Lumen bonding would be expected to reduce the flexing of the fiber wall and, consequently, stress concentration. It is evident that further work at the high compacting stress levels is required to explore the possibilities of this procedure.

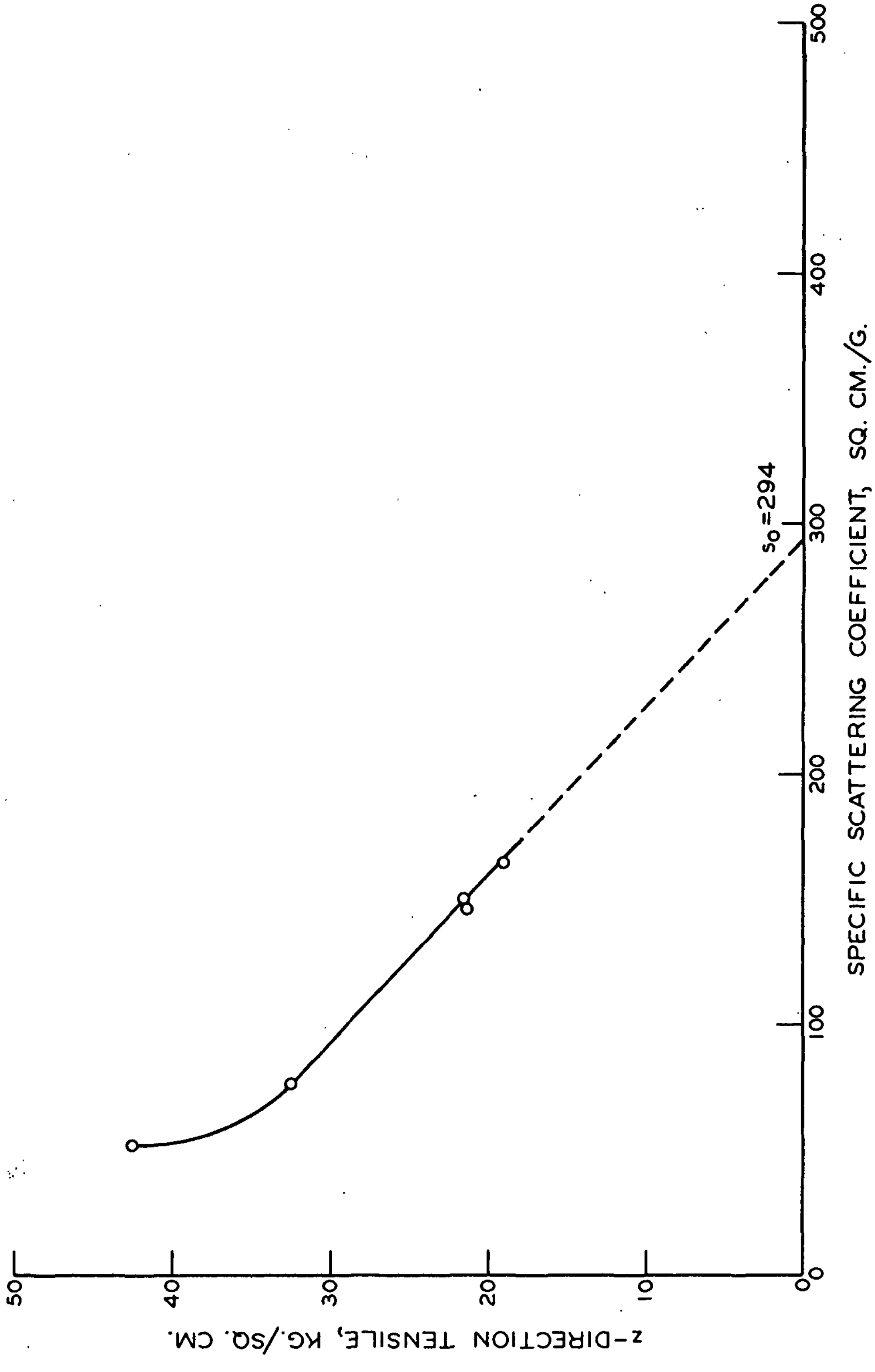


Figure 8. Relationship Between the Specific Scattering Coefficient and z-Direction Tensile for Pressure-Dried Handsheets, Series 2

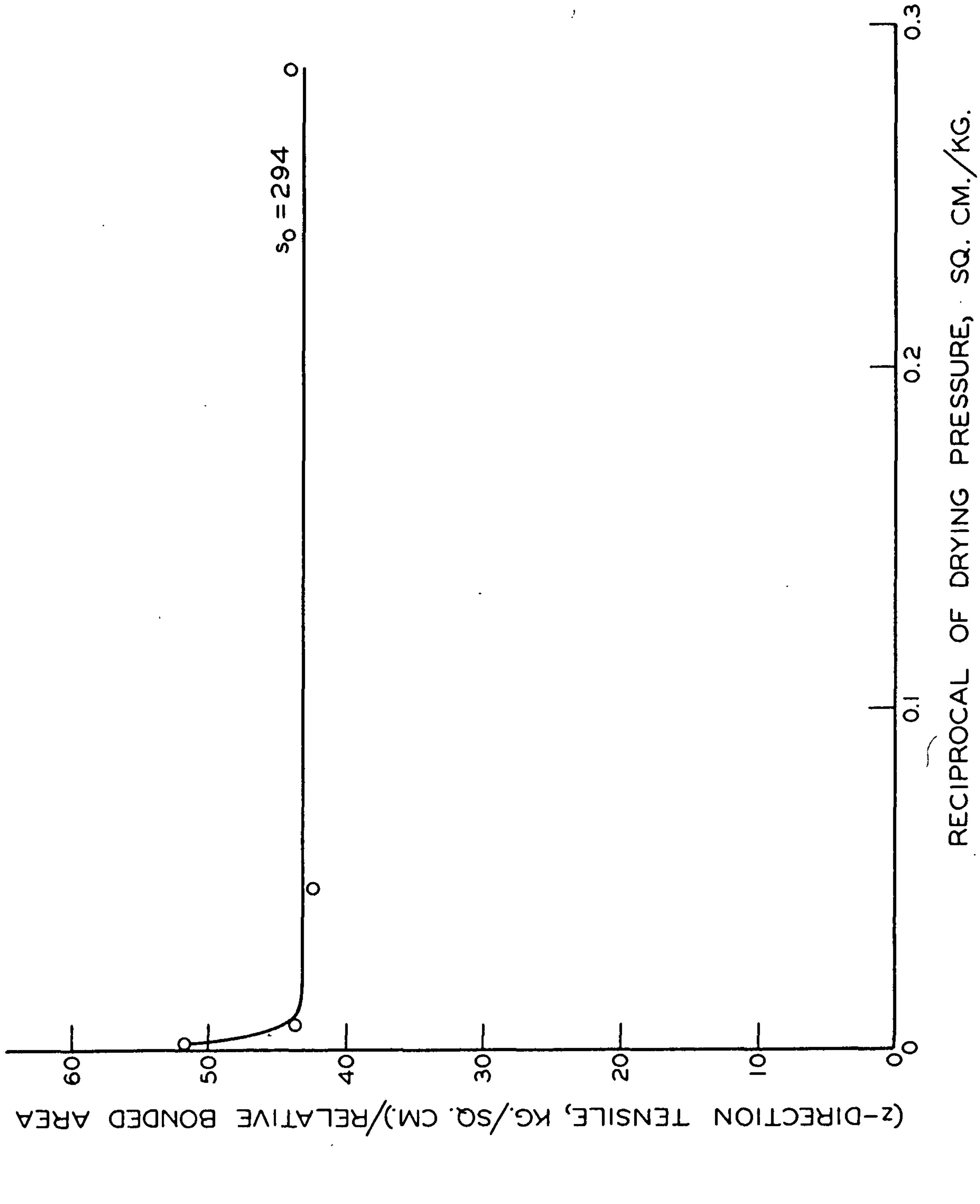


Figure 9. Relationship of Compacting Pressure During Drying to z-Direction Tensile per Unit Bonded Area

LITERATURE CITED

1. Gallay, W., and Lyne, L. M. Studies on the fundamentals of wet web strength. Tappi 37, no. 12:698-704(Dec., 1954); Pulp Paper Mag. Can. 55, no. 11:128-34 (Oct., 1954).

2. The IPC line-type specimen clamps. Research Bulletin of The Institute of Paper Chemistry, 26, no. 2:56-9(Dec., 1959). To be published in Tappi.

THE INSTITUTE OF PAPER CHEMISTRY

Roger H. Van Eperen

Roger H. Van Eperen
Research Assistant

W. A. Wink

W. A. Wink, Chairman
Paper Evaluation Section